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Heap Leaching Literature Review

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RÉSUMÉ

Le présent rapport revoit la documentation disponible sur la récupération de l'or par lixiviation en tas avec une solution de cyanure et étudie de façon plus particulière l'application de cette technologie en régions froides. Il examine surtout les problèmes techniques relatifs au traitement, au confinement et à l'élimination des déchets et les solutions permettant de réduire le plus possible la pollution des eaux souterraines et des eaux de surface et de minimiser les problèmes environnementaux apparentés. A partir des informations obtenues, nous avons décrit la technologie utilisée et nous avons revu les principaux aspects relatifs à la conception des installations. Nous avons également étudié les règlements appliqués en matière de protection de l'environnement ainsi que les méthodes de lutte utilisées dans cinq zones relevant de compétences différentes. Nous avons fait état de l'effet du temps froid sur la conception des installations et sur les opérations, chaque fois que de telles informations étaient disponibles.

Selon les résultats de cette étude, la distribution et la récupération des solutions sont des activités difficiles à réaliser lorsque la température est inférieure à 0 °C. Diverses techniques, comme l'enfouissement des conduites et le chauffage des solutions, ont été mises au point pour contourner cette difficulté, mais, dans la plupart des cas, il faut cesser les opérations durant la période de l'année où la température est inférieure à 0 °C pendant plus de 65 % de la journée. Selon une publication, la saison de lixiviation au Yukon ne devrait pas, compte tenu de ces contraintes, être beaucoup plus courte que celle dans les installations existantes au Nevada. De nouvelles techniques, comme la lixiviation dans des bassins aménagés directement par excavation, ont été proposées pour les régions froides, mais il n'a pas été établi qu'elles étaient commercialement rentables.

Il existe peu de renseignements sur les aspects environnementaux de la lixiviation en tas en régions froides. Le concept selon lequel il est essentiel de confiner la totalité des solutions de cyanure pour assurer la protection de l'environnement s'applique tant en régions froides qu'en régions chaudes. Le confinement et/ou le détournement des eaux de ruissellement produites par la fonte de la neige constituent une exigence spéciale qu'il y a lieu de respecter lors de la conception des installations de lixiviation en tas en régions froides.

Les procédés de traitement des déchets applicables aux eaux excédentaires produites lors de la lixiviation en tas seraient les mêmes que ceux utilisés dans d'autres procédés miniers faisant appel au cyanure. Dans la plupart des installations de lixiviation en tas, le bilan hydrologique est négatif; on ne procède donc pas régulièrement au traitement et à l'élimination des solutions de cyanure. Selon certains rapports faisant état de projets de lixiviation en tas au Yukon, la situation serait la même dans cette région.

Il est essentiel de manipuler et de stocker le cyanure de façon appropriée, mais les exigences de sécurité applicables à la lixiviation en tas en régions froides ne devraient être guère différentes de celles appliquées aux installations classiques de cyanuration.

HEAP LEACHING LITERATURE REVIEW

1 Introduction

This report has been prepared in accordance with the terms of DSS contract no. A7135-6-0031/01-ST. It presents the results of a review of the literature on heap leaching for gold recovery, with emphasis on references essential for understanding the application of this technology in cold climates. The review focuses on engineering problems and solutions for waste treatment, containment, and disposal to minimize pollution of ground and surface water resources and associated environmental concerns.

We begin with a description of the technology, and then list the activities which would be executed in system design. The effects of climate on the design decisions and system performance are reviewed. Information which has been gathered on environmental aspects is summarized with reference to the design and operation. Finally, we give case histories for some recently constructed operations with particular interest in application of the concepts to the Yukon situation.

2 Description of the Technology

Major areas of mineral processing technology rarely result from the efforts of one individual or research group. Rather, they evolve from the efforts of many operators, as different concepts are tried to meet the varying situations which are met from property to property. This is certainly true of cyanide heap leaching for precious metals, which has many of its roots in operating practice at copper oxide acid heap leach operations.

Nevertheless, it may be said that the U.S. Bureau of Mines was instrumental in the popularising, if not the inventing, of cyanide heap leaching for precious metals, and their research contributed several new process options to the technology [1].

In this reference, Heinen et al give a good general description of the process, including the process chemistry, testing methods, commercial practices, and some U.S.B.M. innovations.

Briefly, heap leaching is defined by these writers as

> the percolation leaching of piles of low-grade ores or mine waste that have been stacked or piled on specially prepared watertight drainage pads for pregnant liquor collection.

The ore is mined and placed on the impermeable pads, either as-mined, crushed, or crushed and agglomerated to collect the

fines and improve permeability. An irrigation system distributes a cyanide leach solution over the ore surface from which it percolates down through the heap to the impermeable base. During its passage through the heap, it wets and chemically reacts with gold and silver mineralization to bring it into solution as the cyanide complexes. The solution is collected by the impermeable base and flows by gravity to a pregnant solution pond. The pregnant solution is reclaimed from the pond continuously and the precious metal content is removed by conventional cyanide solution processing methods (usually by adsorption on activated carbon or by precipitation with zinc dust).

Some other good general descriptions of precious metal heap leaching technology should be noted. Clem [2] provides detailed test procedures, operating techniques, and some economic information.

van Zyl [3] describes a zinc precipitation system (Merrill-Crowe process) in which process control is provided by computer monitored analytical system which is suitable for integrating with small heap leach operations.

3 Design of Heap Leaching Systems

3.1 General

Design decisions for heap leaches are extensively influenced by two controlling factors: the ore grade, and the amenability of the ore to leaching as predicted from mineralogical and chemical analysis and demonstrated by process testing.

Ore grade influences the degree of processing which can be economically accomplished: a higher ore grade contains more value per ton to pay back invested capital as well as sustain higher operating costs resulting from more involved process schemes. At higher ore grades, the incremental recovery obtainable by further processing is more likely to justify the increased expense. Thus, heap leach ores tend to be below 3 g/t, while agitation leach feeds tend to be above 4 to 5 g/t. There is a considerable grey area in which either technology may be considered depending on the actual metallurgical behaviour of the feed, and site-specific circumstances.

Amenability testing determines in the first place whether the ore can be economically processed by this technology at all. Since the technology is directed towards the lowest grades of ore, if apparent amenability to the technology cannot be demonstrated, probably the term "rock" should be substituted for "ore" and the project should be abandoned.

If amenability is demonstrated by initial testwork, the program should be extended to include testing which optimises the design and generates all the data necessary for basic engineering and a detailed feasibility study.

3.2 Leaching Concept

Within the general area of heap leaching technology are a number of alternative schemes to consider [4].

3.2.1 Choice of Lixiviant

As far as we can determine, all commercial precious metal heap leaching operations use cyanide solutions as the lixiviant. However, two lixiviants that have been promoted for gold leaching generally are thiourea and Bio-D.

Thiourea has been successfully demonstrated on a laboratory scale for ground minerals and has achieved some limited commercial success [5]. Its principal advantages are much improved leaching kinetics and potentially less toxicity. It operates in an acid system, which may limit its use on ores having high acid consumption characteristics.

A major drawback with thiourea for heap leaching would appear to be its lability in the presence of oxidants such as ferric iron, which are necessary for the leaching reaction. The use of sulphur dioxide as an additive to limit the oxidation of the thiourea is successful in controlled leaching situations [6]. However, the heap leaching process is less well controlled, and it is possible to visualize difficulty in achieving the desired

level of sulphur dioxide during sprinkling operations and within the heap. Reagent consumptions could then rise dramatically.

The advantage of rapid chemical kinetics found with thiourea may not contribute much in a heap leaching situation where extraction rates are more likely to be controlled by physical factors such as solution distribution and diffusion of the chemical species into and out of the crushed mineral.

Bio-D is a proprietary reagent introduced a year or so ago as the likely replacement for all cyanide processes in operation. Despite considerable promotion, it has not achieved the prominence predicted for it. Contacts we have had with labs who have evaluated it indicate that its effectiveness as a lixiviant is in question for some ores and concentrates.

Apparently, it is a bromide-based leaching system, using an organic bromine-containing compound as the oxidant. Bromide ion is the complexing agent used to hold the oxidized gold in solution. Bromide systems were in use for gold leaching before the advent of cyanide leaching, which replaced them due to more favourable performance.

We would regard use of either of the alternates to cyanide as in the realm of new technology development. In specific cases, there might be incentive to use them, but generally, cyanide will be the lixiviant of choice.

3.2.2 Crushing and Agglomeration

First, there is the question of whether to crush, and then, to what extent. This is a decision based on testwork, which will

indicate the potential extra recovery obtainable from each incremental amount of crushing. The engineer uses these results together with cost information to determine at what point the cost of further crushing will not be repaid by the extra recovery. He must bear in mind that crushing to too great an extent may generate an excessive amount of fines which can reduce permeability and/or promote solution channelling in the heap. Thus, while fine crushing may yield better extraction in controlled laboratory testing, control in the field is much poorer, and the hoped-for enhancement may not be achieved.

A better indication of the likelihood of this type of problem will be obtained if a pilot heap test is run, which more closely simulates the full scale operation [7].

Where permeability problems are indicated by high fines or clay content, agglomeration of the fines onto the coarser particles using portland cement or lime may be incorporated at the end of the crushing circuit [8][9].

3.2.3 Temporary vs Permanent Heaps

A decision must be made on whether to establish permanent heaps which will not be moved after completion of leaching, or instead to provide temporary heaps which will be moved to a permanent disposal area subsequently.

The cost of the site preparation and establishment of an impermeable membrane must be borne solely by the ore above it in a permanent heap, whereas in a temporary heap, the leach pad cost can be written off over many more tons because of the continual replacement of ore. Conversely, the cost of the base for

temporary heaps will be greater, since a more robust design is normally selected in this case to withstand the rigors of equipment loading and removing ore.

The more quickly the ore can be leached and replaced, the lower will be the cost of the base for the temporary heap per ton of ore leached, and thus the engineer looks for testwork demonstrating high extractions that are obtainable in relatively short times when deciding to establish a temporary heap leaching system. This system has a higher capital cost, and so will be favored by higher grade and high capacity operations.

This system also permits the establishment of more elaborate ore placement facilities [10] which can be very significant in optimising heap permeability and reducing solution channelling [11][12].

Lower grade ores are more likely to be processed at run-of-mine size, and thus exhibit longer leaching cycles. Hence, they will more usually be treated on permanent heaps.

3.2.4 Lift Height

The cost of base preparation for a permanent heap can be written off over more tons if the heap can be made higher, or if subsequent lifts of ore can be leached on top of the first lift.

The optimum depth of ore for a lift may be indicated by laboratory column tests, but will likely be adjusted in full scale operation to obtain the best results. Because this parameter is significant to the economics, this is another reason to run one or more pilot heaps prior to completing the

feasibility study.

The potential for adding subsequent lifts is also best determined by field tests. Experience varies on this, with some operations reporting reduced extractions with subsequent lifts [13], and others finding it to be a successful approach [14].

3.3 Site Selection

Since one of the more significant operating costs is the movement of ore onto and off of the bases, the site should be selected as close to the crusher as possible, which in turn should be near the mine.

The final heap base needs a slope of at least 3 % to promote drainage of the pregnant solution to the edge of the heap for collection. Subject to detailed hydraulic calculations, the heap surface needs the same gradient to provide equal pressure to all the sprinklers.

These grade requirements do not preclude the construction of heaps in mountainous terrain, or necessitate extensive cut and fill activity in such areas. The heap surface must still be near level for the sprinkling piping, but the base can be sloped, resulting in a terraced design, whose average depth is optimised as discussed above. Such a design may not make the best use of the prepared base, because of the varying lift height which is subject to a maximum, but it can be successfully implemented [15].

3.4 System Sizing

Once the leaching concept has been settled, the engineer must size the heaps and the associated processing equipment to match the projected mining rate of ore. In either the permanent or temporary concept, the leaching is carried out according to a cyclic sequence of activities. In the temporary heap approach, the cycle is quite rigid, since clean heap bases must be available to accept mined ore on a regular progression. With permanent heaps, the construction of new bases is on-going, and the actual leaching cycle can be more flexible to match leaching time to leaching characteristics of the ore, with less reference to the mining rate.

Constraints on leaching time in a permanent heap system do exist, however. A longer cycle time implies a greater tonnage of ore under leach at any time for a given feed rate. There is thus a greater area to irrigate, and the pregnant solution flow is greater. The limitations to increasing the leach time are then determined by the available pumping and irrigation capacity on the one hand, and the capacity of the precious metal recovery plant to treat pregnant solution on the other.

The latter constraint can be alleviated somewhat by using the pregnant solution produced from one heap to irrigate another, thereby increasing its precious metal concentration without adding a greater volume to process. However, this is not always a successful policy; the inevitable solution losses are more costly with a more concentrated solution, and some ores have a tendency to "rob" gold and silver from concentrated pregnant solutions so that the hoped-for concentration increment is not

achieved.

3.4.1 Activities in the Cycle

The leaching cycle varies somewhat depending on the approach taken at a particular property, but in general the following activities may take place:

1. Charge heap with ore.
2. Cross rip to destroy compaction.
3. Place irrigation piping.
4. Leach.
5. Wash to recover chemicals and for environmental protection.
6. Remove irrigation piping.
7. Remove ore to disposal area.

The final step would not be present in a permanent heap system, but a base preparation activity would be required before ore placement.

3.4.2 Matching Mining Rate to Leaching Cycle

In order to operate the cycle and match it to the mining rate, the heap area is divided into a number of sectors [16]. A sector

is an area that can be conveniently sprinkled by a module of irrigation piping and sprinklers.

From the sector area and depth, together with the ore bulk density when placed, the tonnage per sector can be calculated. When this is known, the annual number of sectors which can be constructed is calculated from the annual mine production.

The actual time required under leach to achieve the desired extraction is estimated from the testing data. Now the following equation holds true (for a 365 day leaching year):

(sectors/year)*(leaching period/sector)
= (sectors leaching at any time)*365

We can therefore calculate the sectors leaching at any time, and from this and the known irrigation rate per sector (usually about 0.01 $m^3/h/m^2$), we can calculate the required flow of barren solution onto the heaps. Applying a factor for losses and wetting of ore based on pilot testing or experience gives the pregnant solution flow.

The expected precious metal production is calculated from the ore treatment rate times the grade times the estimated recovery. This production rate is divided by the solution flow rate to obtain the average solution grade. This provides the basis for the precious metal recovery process sizing.

By substituting the total estimated cycle time per sector for the leaching period per sector in the above equation, the total number of sectors either in preparation, leaching and washing, or being dismantled can be estimated. This tells how many sector

bases must be constructed to operate a temporary heap system in continual rotation.

3.4.3 Precious Metal Recovery Processes

Precious metal recovery usually comes down to a choice between carbon adsorption in fixed or fluidized bed columns, and zinc precipitation. With carbon adsorption, a number of stripping methods are available, with precious metals usually recovered from the strip solution by electrowinning. Zinc precipitation may also be used to recover the precious metals from carbon strip solution, although this is not as common.

Carbon adsorption systems are sized largely on precious metal throughput, while zinc precipitation systems are sized based on solution flow. Thus, as a generalization, carbon systems will be used on lower grade solutions produced in larger volumes, whereas zinc precipitation will be used on higher grade solutions of more limited flow rate.

As well, solutions high in silver will more likely be processed by zinc precipitation [17]. Carbon adsorption system size is based on ounces throughput, whether ounces of silver or gold. High silver content will require a large carbon plant, but because of its relatively low value, the silver recovered is less able to bear the capital cost of the plant. Accordingly, the silver is preferably recovered by zinc precipitation, where its presence in relatively large amounts has lesser effect on plant size and cost.

A process for silver sulphide precipitation has been proposed by the USBM as a means of lowering the silver content of pregnant

solutions fed to a carbon plant [1].

The electrowon precious metals or zinc precipitate are finally smelted to dore metal, an alloy of gold and silver. Dore bars are then usually shipped to a refinery for further purification.

4 Operation in Cold Climates

4.1 General

Part of the object of the present review is to develop information pertinent to the operation of the technology in cold climates such as would be encountered in the Yukon. Apparently, there are "six to eight exploration targets which could have potential for heap leach gold mining now in some stage of exploration in the Dawson Range Gold Belt" [18].

Temperature has an effect on both mass transfer and chemical kinetics, so that some effect on leaching efficiency might be expected. In practice, performance is limited more by the difficulties in efficiently contacting the ore with solution than by the leaching reactions themselves. This is true especially in freezing weather, which makes solution distribution and collection a problem. Published discussions of heap leaching in cold weather invariably focus on the latter activities.

While there is limited Canadian experience with cyanide heap leaching [19], a large body of information has been published based on U.S. experience. Many of the U.S. operations are located at high elevations, so that most of the cold weather problems have been dealt with in one way or another. Pegasus' Zortman - Landusky operation in Montana is an extremely large and low grade operation which is profitable in spite of being limited by climate to a leaching season of seven to eight months per year

[20].

A number of writers have proposed this type of operation for the colder parts of Canada and Alaska [21][22][23].

Thorndycraft [4] has dealt with the subject directly based on his experience as Mill Superintendent at the Pinson Mining Co. heap leaching operation. The Pinson operation is located in Northern Nevada at 4900 feet elevation. He identifies two weather conditions that inhibit heap leaching as extreme cold and extreme rainfall. High rainfall may impact on the way the leaching is conducted, but not on its feasibility.

Thorndycraft strongly advocates the suitability of the technique for Canada. Based on its low capital costs, many of the problems can be obviated by seasonal operation. Techniques such as irrigation only during the sunny portion of the day, or solution heating are suggested to extend the leaching season.

In his paper, a map of Canada is presented showing the areas where suitable temperatures exist for heap leaching for at least 200 days a year. Thorndycraft defines suitable temperatures to mean 8 or more hours per day above freezing, although this would vary depending on solution temperature, irrigation method, and other site specific factors. It includes little of the Yukon, but the selection of 200 days must be regarded as arbitrary, and the true seasonal requirement would need to be determined in each case by a technical - economic study. Seasonal operation of heap leaching in the Yukon ought to be feasible in the same way as seasonal operation of placer mining.

Rainfall can be a problem in that it contributes to solution inventory in the process. Normally, evaporation and losses in

leached tailings result in a negative water balance with (quite often) a significant water demand. Zero discharge is the rule. In an area of high rainfall, this might not be possible, and a need to dispose of cyanide-containing solution could arise. Further, high rainfall could mobilize residual cyanide in tailings before it was eliminated by natural mechanisms.

Apparently, in the areas of potential application in the Yukon, high rainfall is considered unlikely to cause problems [24].

4.2 Solution Management in Cold Climates

In areas where seasonal operation is practised due to cold winters, the end of leaching is dictated by the inability to adequately distribute and recover the solution due to freezing problems. Cold solutions exhibit slower leaching kinetics [22], but this, in itself, would probably not provide cause to shut down operations in winter.

Freezing in distribution and recovery piping can be dealt with by either shutting the system down during periods of cold weather, or by burying the pipe [25]. Final distribution of the solution to the heap surface is usually by means of sprinklers. Mechanical impulse-type sprinklers are subject to jamming from a number of causes, including ice [10] resulting in areas of the heap going unwetted.

Senninger Wobblers are extensively used to distribute solution. At Smoky Valley [26], located about 100 km north of Tonopah, Nevada, it is found that in winter, a dome of ice builds up over the wobblers, but that the sun will melt this during the day. This operation also heats its solution to obtain a longer

leaching season, and is able to operate for 9 months of the year. In cold weather, spraying is also restricted to daytime at Ortiz [27]. Ortiz is located between Santa Fe and Albuquerque, New Mexico, near the town of Cerrillos. Ortiz also tried solution heating, in their case with submerged combustion, directly in the process solutions [28]. Absorption of carbon dioxide by the solutions led to carbonate precipitation scaling problems, and the system was abandoned.

Freezing problems may be alleviated where solution is distributed by ponding, but this technique has a reputation of promoting solution channelling [25], and does not provide the certainty of even distribution that can be obtained by sprinkling techniques. Ponding is usually taken as an indication of poor permeability in the heap, and to achieve it might mean either pumping unusually high rates of solution onto the surface or intentionally reducing the permeability by, for example, compaction. The latter runs counter to the accepted procedures which have been shown to lead to successful operations.

Another distribution approach which has been adopted in copper dump leaching is the burying of vertical perforated plastic pipe sections at intervals in the heap [29][30]. The solution is directed into these and is distributed through the perforations. Because the distribution is not exposed to the air, freezing problems are reduced. However, holes must be drilled in the heap to accommodate the piping, making installation more expensive.

Equally, this technique cannot ensure solution contact with the ore at the top of the heap between the pipe sections. It is more satisfactory in copper heap leaching where the depth of burial is a relatively small fraction of the total dump depth, so that the ore which is missed is a less significant fraction of the total.

A vat leaching technique using existing excavations in the ground provides an alternate approach [31]. Flooding the ore from the bottom both ensures good solution contact and reduces the difficulties of freezing during solution distribution. Whether the proposed system offers any economies over conventional vat construction would need to be the subject of an engineering study related to a specific situation.

Environmental problems associated with this approach would be related to escape of cyanide solutions into the groundwater, as elimination of sprinkling means no losses to the air should occur. Some type of lining for the excavation would be required to ensure no losses, and the degree of confidence in such a system could be increased by adopting more expensive designs. Disposal of the leached tailings leads to the same concerns as are encountered with conventional heap leaching, except that in this more carefully controlled operation, washing of cyanide from the rock should be more complete.

5 Environmental Aspects

The assessment of environmental impact and regulation of heap leaching operations is similar to other mines and industries handling hazardous materials. The primary concern of most regulatory agencies is potential impacts on groundwater and surface water associated with the use of sodium cyanide. Mining companies must demonstrate that the facility is designed to contain cyanide plus handle most emergencies.

Gold is recovered from the gold cyanide complex in the pregnant solution from heap leach operations in most cases by activated carbon adsorption, although some operators use zinc precipitation (Merrill-Crowe process) for various technical and economic reasons. Both recovery processes yield a barren cyanide solution which is recycled to the heap. The chemistry of cyanide is well documented in the literature [32][33][34][35].

Cyanide does not persist in soils due to a combination of physical, chemical and biological mechanisms. Due to its reactivity, the cyanide ion (CN^-) readily forms complexes with metals. Iron reacts with cyanide to produce very stable complexes which can form insoluble precipitates. At neutral pH, cyanide complexes release free cyanide ion which reacts with hydrogen ion (H^+) to form HCN gas which can be removed from solution by volatilization. Cyanide can also be oxidized biologically by a wide variety of bacteria [36][37]. There is some evidence that cyanide will remain in abandoned heaps in arid

environments without moisture present, since water is essential to accomplish the release of HCN to the atmosphere [37].

Two previous literature reviews [32][38] provide information on the fate, persistence and degradation of cyanide both in soils and in groundwater. The toxicity of cyanide in the aquatic environment is documented in reference 33. In the present review, a number of articles mentioned requirements for groundwater wells to detect leaks [22][27][39], although no references were located which indicated that contamination of groundwater from heap leaching is a problem.

A method for sampling un-saturated groundwater under liners using lysimeters was described by Bond and Rouse [40]; however, this system is considered impractical by H. Van Drielan [41]. Depth to the water table can be significant in some locations, eliminating groundwater monitoring as a leak detection method.

Regulatory requirements on liners vary between jurisdictions, with no consensus on clay liners versus synthetic membranes; each liner method has advantages and disadvantages. Double liners are reportedly required in California [42].

Regulatory agencies rely on submission of design reports with permit applications coupled with inspection during construction as a standard requirement to demonstrate full containment.

Environmental regulations specific to heap leaching have not been established in either Canada or the US as of the date of this review. Operations are administered based on existing regulations for conventional mining operations and for industries handling hazardous chemicals.

Summaries of regulations and environmental controls currently utilized in four jurisdictions are outlined in the following sections.

5.1 Nevada

Nevada has the largest number of heap leaching operations in the US. The state currently administers on a case by case basis, but will likely be drafting regulations in the near future [41]. Regulatory input focuses on the design and control, rather than detection. Discharges to the environment have not been permitted to date, since all operations are in areas with negative water balances. (Supply of sufficient quantities of makeup water significantly restricts the scale of some operations.) However, future applications in high elevation areas may involve discharges due to snow melt and leach solution melt in the spring.

Rainfall in Nevada typically occurs as storm events. The regulatory authorities generally require storm water capacity sufficient to accommodate the 24 hour 25 year return period storm. Storm events greater than the 25 year event are not considered to pose a serious environmental hazard. The application of leach solution would naturally stop during a major storm, and cyanide remaining on the pile should be diluted. The receiving environment would also be providing a substantial amount of dilution during a major storm.

Flood protection involving diversions, etc. must be designed to the 100 year peak flood. Liners are required under pregnant

and barren solution ponds, while liners may not necessarily be required under pads if clay is used, and if the depth to groundwater is significant.

Ground water monitoring is required only where the groundwater depth is less than 50 feet. A piezometric network can be required to indicate the groundwater depth and relative changes in slope configuration, and is considered an early warning system for leaks. Nevada prefers to see designs that involve free draining pads to avoid having any hydraulic head on the liner; this reduces the potential for loss of solution.

A permanent closure procedure is required to remove cyanide from the heap by rinsing with water prior to moving the tailing from the pad of a temporary heap. The rinse water is either evaporated or used as makeup water. Permanent heaps do not require rinsing since "natural degradation" will reduce cyanide.

5.2 Idaho

The Idaho Department of Health and Welfare has drafted a set of "Rules and Regulations for Ore Processing By Cyanidation", that will be used to issue permits to and regulate future heap leaching operations in that state [43][44].

To date, Idaho has reviewed applications for approximately six heap leaching operations under existing rules and regulations. These operations have been evaluated on a case by case basis. Land application of excess water at a total cyanide value of 0.2 mg/l has been permitted and is preferred for areas with positive

water balances. In addition, provisions are required for storage of storm water. It is recognized that future operations may have to discharge excess treated water to a water course in areas with positive water balances, but without potential land application sites.

The draft rules and regulations specify

1. a registration procedure for existing operations and

2. the supporting information requirements for new permit applications.

A procedure for processing the application involving public and administrative review is provided. Minimum design standard for containment is the 100 year, 24 hour storm event; as well, snowmelt must be considered in the estimates. Impoundment facilities for cyanide solution must be designed for leak detection and recovery. Detailed specifications are listed for design of the liners and procedures are outlined for both abandonment of tailings and seasonal closure. Operations are required to secure bonding or other financial assurance for permanent closure of the facility.

5.3 New Brunswick

The second heap leaching operation in Canada started in June 1986 at Gordex Minerals Ltd.'s Cape Spencer mine near Saint John, N.B. B.P. Selco's Chetwynd mine in Newfoundland was Canada's first [19].

Discussions with the Cape Spencer Mine Manager Mr. Hal Pawson [45] provided information on the environmental and cold weather aspects of the project. The mine is in an area with a 1.7 net positive water balance; therefore, a treatment system using hydrogen peroxide oxidation is used to treat excess process water. Discharge specifications are similar to other mining operations in Canada. Regulatory requirements included provision for a storm pond to store excess water from the barren pond.

The Cape Spencer mine operated for 180 days during the past season but plans to operate 335 days next season by modifying to a system similar to vat leaching. Ice formation during winter operation is not considered a problem by the Mine Manager based on his observations in Nevada at temperatures as low as -10 F.

Groundwater under the ponds is monitored using perforated pipe which drains to a well. Water collects only when it rains. The system checks for leaks in the synthetic liner.

The mine is required to cease operation during high wind conditions; however, the surrounding soils are acidic which assists natural degradation of cyanide resulting from wind losses. A series of pans around the site are used to monitor drift. According to the Mine Manager, cyanide has not been detected at any appreciable concentration in the pans [45]. It is essential to minimize cyanide losses from an operational point of view since recycle cyanide solution may contain gold plus chemical costs for cyanide make-up can be significant.

The Gordex operation has demonstrated that heap leaching is feasible in an area which can be windy, subject to high rainfall and cold weather conditions.

5.4 California

Health and safety aspects of heap leaching operations in California are outlined in a paper prepared by Cole and Kirkpatrick [37]. In California, operating permits are required from a number of local and state agencies regarding water and air quality, hazardous material transportation, storage and use, and occupational safety. Regulations are extensive and can change from jurisdiction to jurisdiction and be site specific.

The California Water Quality Control Board (CWQCB) requires zero discharge from heap leach operations. Areas with high precipitation and surface runoff are a major concern, since "zero discharge" is difficult to attain. In addition, the facilities must be protected from flooding, inundation, and erosion resulting from storms (100 year return). All contaminated water must be stored on site and a treatment system for emergency spills must be in place. Pads and ponds must have liners with a permeability of 1×10^{-6} cm/sec or less. By comparison, the recent draft Idaho rules and regulations specify a permeability of 10^{-7} cm/sec with a minimum thickness for clay liners of 12 inches. CWQCB must approve designs and construction before leaching starts. The Control Board also specifies conditions for abandonment of tailings and handling methods for cyanide.

5.5 Health and Safety

Fortunately the mining industry has extensive experience handling cyanide safely. Few problems have been reported, since mine personnel have respect for the toxicity of cyanide, and strict controls have been established for transportation, use and disposal of this chemical [37][41].

The gold extraction process should be operated as a closed circuit. The greatest potential for harmful exposure comes from improper handling and disposal which could result in spillage and formation of poisonous HCN gas [37]. Personnel involved in heap leaching operations regardless of location will require proper training and experience to ensure an environmentally secure operation. Regulatory personnel will also require adequate training and experience in order to administer heap leaching operations.

5.6 Summary

Little technical information is available concerning the environmental aspect of cold weather heap leaching operations although several mines in high altitude areas of Nevada, Montana, and Idaho experience freezing temperatures during operation. Experience gained at these operations plus the Gordex Minerals Cape Spencer mine will assist in evaluating the environmental aspects of cold weather heap leaching applicable to the Yukon. The concept that total containment of cyanide solutions is essential to provide environmental protection applies to both cold and warm weather operations.

Winter operations can accumulate ice on heaps which will melt when air temperature increases; however, as long as sufficient storage is available for melt water, a discharge of untreated water should not take place. All operations must have liners under the pads and solution ponds and must have a method of detecting leaks if practical.

Heap leaching operations should have the capacity to treat excess water produced during storms, especially if storm water storage capacity is limited. Waste treatment processes applicable to treating excess water from a heap leaching operation would be the same as for other mining operations using cyanide. In fact, this excess water from heap leaching operations should not be difficult to treat since it will consist of a clear solution with low cyanide concentrations and will contain very little iron or sulfides which can cause treatment problems.

Proper handling and storage of cyanide is essential, but the safety requirements should not differ from requirements applied to conventional cyanidation plants.

Design review and inspection by the regulatory agencies prior to commencing operation is essential; leak detection after startup should not be relied upon due to the technical difficulties involved in sampling.

Emergency procedures, operation plans and abandonment plans should be formulated prior to commencing operation. In addition, the operator should be required to demonstrate sufficient training and experience to handle cyanide in a safe and environmentally secure manner.

The design of the facility should consider net water balance, wind conditions, and the environmental impact of leaks and spills.

6 Case Histories

6.1 Introduction

Two case histories are provided to give further insight into how the technology could be applied in the Yukon. The first is the Alligator Ridge project in Nevada. At present, there does not seem to be any information suggesting that an operation in the Yukon would differ significantly from one such as Alligator Ridge, except probably in the length of the operating season. At an ore processing rate of 680,000 tons per year [46], this is somewhat smaller than the size of operations now being contemplated in the Yukon [18]. However, good information is available, and the relatively dry climate with a significant period of subfreezing temperatures gives a useful pattern to study.

The second case examined is intended to represent a much smaller operation such as might be operated on higher grade ores by individuals on a seasonal basis rather than by a larger mining company. We provide this case history because of the similar scale and management concept to smaller seasonal placer operations now existing in the Yukon. The operation is not named, but is described by the U.S.B.M. as an example of the application of agglomeration technology [8].

It should be noted that we are not suggesting that placer deposits could be treated by heap leaching technology. Placer

gold deposits by their nature contain relatively coarse gold that would be expected to leach slowly, and is best recovered by gravity methods.

6.2 Alligator Ridge Project

6.2.1 General

The Alligator Ridge mine is located in a remote area 110 km northwest of Ely, Nevada. It was discovered in 1976 by a prospector under contract to Amselco Minerals Inc [12]. Following design and feasibility studies, bids for engineering were sought at the end of 1979, and the process was operational in September, 1980.

Initial project criteria showed ore reserves of 4,400,000 tonnes at 3.4 g/t leachable Au. Mining was to take place at 680,000 t/y for a life of 6-1/2 years. Leaching was scheduled for 250 days per year, with a projected annual output of 1900 kg Au in dore bullion. The facilities represent an investment of $US 30 million.

6.2.2 Development

Exploration began in 1977 with mapping and trenching, leading to a percussion drilling program later that year. The drilling over the next year delineated three mineralized zones which formed the basis for a feasibility study in early 1979. Bench scale studies showed high recoveries from the relatively porous siltstone ore in heap leach simulations, and the ore was

relatively free of cyanicides. Heap leaching was tentatively selected as the processing method, and two pilot tests were run to confirm scale-up predictions based on the lab data. In one test, agglomeration was attempted with water only, while in the second, portland cement and sodium cyanide were added as well. Both heaps yielded about 80 % extraction, with a somewhat higher rate initially from the cement agglomerated test. Final studies confirmed heap leaching as more economic than conventional milling and agitation cyanide leaching.

As mentioned above, a fast-track engineering and construction schedule permitted full operation eight months after the decision was taken to proceed. This short lead time can be a significant advantage for the heap leaching process when deciding among process alternatives.

6.2.3 Heap Construction

Ore is crushed to -19 mm in a three stage crushing circuit, and is then agglomerated with water, cyanide, and lime in a rotating drum agglomerator. The leach pad area was excavated adjacent to the permanent crushing plant. The base consisted of three separate 100 mm layers of silt, compacted to 90 % of maximum dry density. Networks of slotted drainage lines covered with coarse gravel were laid on top of the silt. These carry the pregnant solution to main collection pipes installed along one side of each heap. These empty into hypalon-lined ditches at the low end of each row of heaps.

The heaps were originally installed as permanent single-use bases. Space limitations, coupled with the high cost of base preparation led to evaluation of reuse of the bases. Studies

concluded that placing subsequent lifts of ore on the existing heaps would decrease the permeability of the in-place material, but drainage characteristics would still be adequate. Consequently, it was decided to place additional lifts on the heaps and to fill in between the existing heaps.

Initial heaps were built to a depth of about 3.5 m by driving on the material and end-dumping from trucks, with final levelling and ripping by dozer. Higher heaps exhibited permeability problems, apparently because some of the compacted ore could not be reached by the ripper. Permeability problems with the initial heaps resulted in the requirement to lower the irrigation rate to reduce ponding and erosion caused by solution run-off.

At the time of construction of additional lifts, the heap construction practise was modified to eliminate any vehicle traffic on the new ore. Lift height was reduced to 1.8 m, and leach performance using the new method has been excellent, with more than 70 % extraction obtained in 30-40 days compared with 60-90 days ore longer previously.

6.2.4 Leach Operations

Leaching operations start in early March, and are forced to stop in late November or early December by freezing conditions.

Impulse sprinklers originally used worked as long the the rotation was not stalled. However, stalling was a constant problem due to inadequate pressure, plugging with scale or trash, wear, or ice formation. Late in 1982, the impulse sprinklers were replaced by Senninger wobblers fitted with individual pressure regulators. The simple design is less sensitive to wear

and freezing. Using this equipment, leaching continued into mid-December 1982 despite temperatures as low as -9 C.

Ripping between solution application cycles provides improved performance. A heap is leached until the pregnant solution grade falls to an uneconomic level. Leaching is halted and the heap is allowed to drain. When dry enough, the heap surface is thoroughly cross-ripped, permitting releaching, or construction of a new lift.

6.2.5 Solution System and Precious Metals Recovery

Pregnant solution flows to the pregnant solution pond which is designed to hold one day's solution plus the equivalent of 75 mm rain on the catchment area of the heaps.

Pregnant solution is pumped to the carbon adsorption columns where it is contacted countercurrently with activated carbon in five fluidized bed stages. Barren solution is recycled to the leaching system after fortification with cyanide and caustic. Carbon is advanced through the columns periodically, with loaded carbon (10 kg Au/t) being transferred to a batch stripping column. Circulation of a strong cyanide solution at 129 - 132 C through the carbon strips off the gold in a period of 10 h. The strip solution is pumped through electrowinning cells where the precious metals are plated onto steel wool cathodes.

In addition to gold and silver, mercury is recovered from the ore by the leaching process, and follows the gold through to the cathodes. This is removed by heating the gold sponge to 650 C in a retort, and condensing the mercury vapours that are produced.

After retorting, the gold sponge is mixed with a borax - sodium nitrate - silica sand flux and smelted to a dore assaying about 92 % gold and 6 % silver. The dore bars are then shipped to a custom refinery.

6.3 Arizona Heap Leach Operation

This small operation described by the U.S.B.M. processes 20 tpd of gold ore at a grade of 7 g/t. Information provided is limited, but serves to illustrate the type of small operation which could be considered for the Yukon.

The ore is described as an oxidized disseminated deposit. The host rock is porous with the gold particles exposed.

The ore is mined from an open pit, transported to the crushing plant by a front-end loader, crushed to -10 mm, and conveyed to a drum agglomerator. The crushed material is agglomerated with portland cement and a sodium cyanide solution. The agglomerated material is conveyed to an impervious leaching pad and stacked into a 7 foot high heap containing 100 tons. A 48 h cure time is allowed prior to commencement of leaching.

The heap is leached in only 5 days by spraying a cyanide solution at the rather high rate of 0.08 $m^3/h/m^2$. (This high rate is probably related to the high grade of the ore, and requires the very permeable heap provided by the agglomeration process.) Pregnant solution is collected and processed for gold recovery in four carbon columns in series, with the resulting barren solution being recycled to the heap.

The loaded carbon is stripped at atmospheric pressure with an

alkaline alcohol solution. Precious metals are then electrowon onto steel wool cathodes. The cathodes are leached in nitric acid to dissolve the iron, and the resulting sludge is smelted to dore bullion.

Gold recoveries in this circuit average 90 %.

7 Summary

A review of available literature on cyanide heap leaching for gold has been completed. With the assistance of the retrieved information, a description of the technology was given, and the major design decisions have been reviewed. A review of the environmental regulations and practices was given for five jurisdictions. Mention has been made of the effects of cold weather on design and operations whereever such information has been available.

The review identified solution distribution and collection as difficult activities to complete under freezing conditions. Various techniques such as buried piping and solution heating have been developed to deal with this situation, but most operations must cease operation for the portion of the year when freezing temperatures persist for much more than 65 % of a day. One publication suggested that the leaching season in the Yukon under this constraint need not be much shorter than at existing operations in Nevada. New techniques such as leaching in vats excavated in the ground have been proposed for cold areas, but not proven commercially.

Little technical information is available concerning the environmental aspect of cold weather heap leaching operations. The concept that total containment of cyanide solutions is essential to provide environmental protection applies to both cold and warm weather operations. Containment and/or diversion

of runoff resulting from snowmelt is a special design requirement for heap leach facilities in cold areas.

Waste treatment processes applicable to treating excess water from a heap leaching operation would be the same as for other mining operations using cyanide. Most heap leaching operations operate with a negative water balance, so that regular treatment and disposal of cyanide solutions is not practiced. References to proposed operations in the Yukon suggested that this would be the case there as well.

Proper handling and storage of cyanide is essential, but the safety requirements for heap leaching in cold climates should not differ from requirements applied to conventional cyanidation plants.

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